

CLAIMS

What is claimed is:

1. Apparatus for net shaping gear teeth of a high performance power transmission gear from a powder metal workpiece comprising:

a source of heat for heating a powder metal workpiece in the form of a near net shaped gear blank having carburized gear teeth surfaces above its critical temperature to obtain an austenitic structure throughout its carburized surfaces;

a first quenching expedient for cooling the workpiece at a rate greater than the critical cooling rate of its carburized case to a uniform metastable austenitic temperature just above the martensitic transformation temperature;

opposed dies, each having an outer peripheral profiled surface, for rolling the gear teeth surfaces to a desired outer peripheral profiled shape while holding the temperature of the workpiece in the uniform metastable austenitic temperature range, the dies being operable such that the gear surfaces first undergo densification by rolling involving substantial compaction of the material in the gear tooth surface layers resulting in a collapse of the pores initially existing near the gear tooth surface region, then plastic deformation as a result of the rolling and sliding movements in the metastable austenitic temperature range with resultant strengthening of the gear teeth; and

a second quenching expedient for cooling the workpiece through the martensitic range for hardening the carburized gear teeth surfaces.

2. The apparatus as set forth in claim 1

wherein the first quenching expedient includes an oil bath maintained at a temperature in the range of approximately 450° F. to 500° F.

3. The apparatus as set forth in claim 1 including:

an enclosure providing an inert atmosphere during the performance of all operations performed on the workpiece.

4. The apparatus as set forth in claim 2

wherein the source of heat includes a first toroidal shaped induction heater defining a first heating zone and a second toroidal shaped induction heater defining a second heating zone; and

including:

a gear transfer mechanism for rapidly transporting the powder metal workpiece from the first heating zone to the second heating zone, then into the liquid working medium;

a support member for rotatably supporting the workpiece within the first heating zone so as to be coaxial with the first induction heater and for rotatably supporting the workpiece within the second heating zone so as to be coaxial with the second induction heater; and

a drive mechanism for rotating the workpiece on its axis of rotation within the first heating zone for a first selected period of time and for rotating the workpiece on its axis of rotation within the second heating zone for a second selected period of time.

5. The apparatus as set forth in claim 4

wherein the actuator mechanism includes:

a support spindle for rotatably supporting the powder metal workpiece;

and

an expansible chuck on the spindle selectively adjustable between a retracted condition for free reception into a central hole of the workpiece and an expanded condition for firmly holding the workpiece on the spindle.

6. The apparatus as set forth in claim 5

wherein the transfer actuator mechanism includes a linear actuator [166] operable for selectively moving the spindle longitudinally between and among an initial fully retracted position, a loading position whereat the workpiece is releasably mounted on the spindle, a first heating position whereat the workpiece is positioned within the first heating zone, a second heating position whereat the workpiece is positioned within the second heating zone, and a quench position whereat the workpiece is submerged in the liquid working medium within the first vessel.

7. The apparatus as set forth in claim 6

wherein the apparatus includes a stationary frame; and

the actuator mechanism includes

a housing for rotatably mounting the spindle;

a lead screw having upper and lower limits rotatably mounted on the stationary frame;

a follower nut threadedly engaged with the lead screw for linear movement thereon between the upper and lower limits, the nut being integral with the spindle housing;

whereby movement of the follower nut is imparted to the spindle with the powder metal workpiece thereon.

8. The apparatus as set forth in claim 5 including:

a through-feed actuator for moving the support spindle between an inactive position and an active position.

9. The apparatus as set forth in claim 8

wherein the opposed dies include:

a first rolling gear die rotatable on a first axis;

a second rolling gear die rotatable on a second axis generally parallel to and spaced from the first axis; and

wherein the support for the workpiece includes:

a lower workpiece support spindle rotatably supported on a third axis generally parallel to the first and second axes within the controlled metastable austenitic environment, and

a through-feed actuator for advancing the workpiece along the third axis in a through-feed direction such that the outer peripheral surface of the workpiece slidably engages the first and second rolling gear dies and continues to advance until the workpiece is positioned substantially coextensive with the first and second rolling gear dies in the through-feed direction.

10. The apparatus as set forth in claim 9 including:

a rotary actuator for simultaneously rotating the first and the second rolling gear dies.

11. The apparatus as set forth in claim 10

wherein the second quenching expedient includes an oil bath maintained at a temperature in the range of approximately 50° F. to 250° F.

12. The apparatus as set forth in claim 1

wherein the powder metal includes an admixture of iron powder and at least one alloying addition.

13. The apparatus as set forth in claim 12

wherein the alloying addition includes at least one of carbon, manganese, silicon, nickel, chromium or molybdenum.

14. The apparatus as set forth in claim 1

wherein the powder metal is composed of steel from the group consisting of AISI-SAE 40XX, AISI-SAE 46XX, AISI-SAE 51XX and AISI-SAE 86XX.

15. The apparatus as set forth in claim 1

wherein the powder metal includes a steel composition having a carbon content less than about 0.2% by weight, the steel composition; and

wherein the step of carburizing is performed prior to the step of hardening.

16. The apparatus as set forth in claim 1

wherein the powder metal comprises a steel composition having a carbon content greater than about 0.5% by weight.

17. The apparatus as set forth in claim 1

wherein the powder metal gear blank is pressed and sintered.

18. The apparatus as set forth in claim 17

wherein densification in the range of 90 to 100 percent of full theoretical density to a depth of about 70 microns and up to about 1300 microns is achieved by applying densifying pressure to surfaces of at least gear tooth root and flank regions of the pressed and sintered powder metal gear blank.

19. A method for net shaping gear teeth of a high performance power transmission gear from a powder metal workpiece, comprising the steps of:

- (a) heating a powder metal workpiece in the form of a near net shaped gear blank having gear teeth surfaces above its critical temperature to obtain an austenitic structure throughout its surfaces;
- (b) isothermally quenching the workpiece at a rate greater than the critical cooling rate of its surfaces to a uniform metastable austenitic temperature just above the martensitic transformation temperature;
- (c) rolling the gear teeth surfaces of the workpiece to a desired outer peripheral profiled shape between opposed dies, each die having an outer peripheral profiled surface, while holding the workpiece at the uniform metastable austenitic temperature, the gear teeth surfaces undergoing densification, plastic deformation, and strengthening as a result of the rolling operation; and
- (d) cooling the workpiece through the martensitic range to thereby harden the surfaces of the gear teeth.

20. The process set forth in claim 19 wherein step (c) includes the steps, sequentially, of:

- (e) radially compacting the material in the gear teeth surface layers resulting in a collapse of the pores initially existing in the gear teeth surface regions with resulting densification of the gear teeth surface regions; and
- (f) plastically deforming the gear teeth surface layers by causing lateral material flow of the gear teeth surface layers as a result of the operation of rolling in the metastable austenitic temperature range.

21. The process set forth in claim 19 including the steps, before step (a) of sequentially:

- (e) pressing the workpiece; and
- (f) sintering the workpiece.

22. The process set forth in claim 19, including the steps, before step (a) of sequentially:

- (e) pressing the workpiece;
- (f) sintering the workpiece; and
- (g) densifying the workpiece.

23. The process set forth in claim 21 wherein step (e) includes the steps, alternatively, of:

- (h) single pressing the workpiece; and
- (i) multiple pressing the workpiece.

24. The process set forth in claim 21 wherein step (f) includes the steps, alternatively, of:

- (h) single sintering the workpiece; and
- (i) multiple sintering the workpiece.

25. The process set forth in claim 21 wherein step (f) includes the step of:

- (g) sintering and hardening the workpiece in an integrated operation.

26. The process set forth in claim 21 wherein step (f) includes the step of:

- (g) sintering, hardening, and carburizing the workpiece in an integrated operation.

27. The process set forth in claim 19 including the steps, before step (a) of:

- (e) pressing the workpiece; and
- (f) sintering the workpiece.

28. The process set forth in claim 27 including the step of:
(g) applying densifying pressure to surfaces of at least the gear tooth root and gear tooth flank regions of the pressed and sintered powder metal gear blank to establish densification in the range of 90 to 100 percent of full theoretical density to a depth of about 70 microns and up to about 1300 microns.

29. The process as set forth in claim 19 for fabricating a parallel axis gear.

30. The process as set forth in claim 29 wherein the parallel axis gear includes at least one of a spur gear, a helical gear, and a double helical gear.

31. The process as set forth in claim 19 for fabricating an intersecting axis gear.

32. The process as set forth in claim 31 wherein the intersecting axis gear includes at least one of a straight bevel gear, a spiral bevel gear, a hypoid gear, a worm gear, and a worm-wheel gear.

33. An article of manufacture fabricated by the process as set forth in claim 19.

34. Apparatus for effecting densification and plastic deformation in powder metal gear teeth of a power transmission gear at an elevated metastable austenitic temperature range, comprising:

a first support member for rotatably supporting on a first axis a rolling die, the rolling die having an outer peripheral contoured surface extending between generally parallel spaced lateral surfaces transverse to the first axis, the rolling die including a plurality of gear teeth, each gear tooth including a tooth flank with opposed involute surfaces and a tooth tip surface;

a second support member for rotatably supporting on a second axis distant from and parallel to the first axis, a near net shape powder metal workpiece having an initial outer peripheral contoured surface and including a plurality of gear teeth, each gear tooth having a tooth flank with a nominally involute surface and a root/fillet region with a trochoidal surface; and

an operating mechanism for rolling the gear teeth surfaces to a desired outer peripheral profiled shape while holding the temperature of the workpiece in the uniform metastable austenitic temperature range, the dies being operable such that the gear surfaces first undergo densification by rolling involving substantial compaction of the material in the gear tooth surface layers resulting in a collapse of the pores initially existing in the near the gear tooth surface region, then plastic deformation as a result of the rolling and sliding operation in the metastable austenitic temperature range with resultant strengthening of the gear teeth.

35. A method of producing net shaped gear teeth from a near net shape workpiece of powder metal having an initial outer peripheral contoured surface, each gear tooth having a gear tooth flank with a nominally involute surface and a root/fillet region with a trochoidal surface, the method comprising the steps of:

(a) rotatably supporting on a first axis a rolling die having an outer peripheral contoured surface extending between generally parallel spaced lateral surfaces transverse to the first axis, the rolling die including a plurality of teeth, each gear tooth including a tooth flank with opposed involute surfaces and a tooth tip surface;

- (b) rotatably supporting on a second axis distant from and parallel to the first axis a near net shape powder metal workpiece having an initial outer peripheral contoured surface and including a plurality of gear teeth, each gear tooth having a tooth flank with a nominally involute surface and a root/fillet region with a trochoidal surface;
- (c) advancing the rolling die in an in-feed direction generally perpendicular to the first and second axes such that the rolling die meshingly engages with the workpiece;
- (d) rotating the rolling die about the first axis while engaged with the workpiece;
- (e) rolling the gear teeth surfaces of the workpiece to a desired outer peripheral profiled shape while engaged with the rolling die having an outer peripheral profiled surface while holding the workpiece at the uniform metastable austenitic temperature, the gear teeth surfaces undergoing densification, plastic deformation, and strengthening as a result of the rolling and sliding operation;
- (f) while performing step (d), maintaining continuous conjugacy between the rolling die and the workpiece with the involute surface of each tooth of the rolling die engaging the involute surface of a mating tooth of the workpiece and the tooth tip of the rolling die engaging the trochoidal root/fillet surface between adjacent mating gear teeth of the workpiece to effect material flow along the outer peripheral contoured surface;
- (g) continuing to advance the rolling die in the in-feed direction thereby deforming the surface of each gear tooth flank and of a corresponding root/fillet region until a final net shape of each gear tooth and root/fillet region is achieved; and
- (h) continuing to perform all of the preceding steps with the rolling die and workpiece meshingly engaged, thereby deforming the involute and trochoidal root/fillet surfaces of all of the gear teeth of the workpiece resulting in a final net shaped gear.

36. An article of manufacture fabricated by the method as set forth in claim 35.

37. The process set forth in claim 35

wherein step (e) includes the steps of:

(i) radially compacting the material in the gear teeth surface layers resulting in a collapse of the pores initially existing in the gear teeth surface regions with resulting densification of the gear teeth surface regions; and

(j) plastically deforming the gear teeth surface layers by causing lateral material flow of the gear teeth surface layers as a result of the operation of rolling and sliding in the metastable austenitic temperature range.

38. A method as set forth in claim 35 including the step, before step (c) of:

(i) advancing the workpiece in a through-feed direction parallel to the first and second axes such that the outer peripheral profiled surface of the workpiece engages the outer peripheral profiled surface of the rolling die and continues to advance until the workpiece is positioned substantially coextensive with the rolling die in the through-feed direction.

39. A method as set forth in claim 38

wherein step (c) includes the steps of:

(i) simultaneously with step (g) after the workpiece and rolling die are substantially enmeshed, advancing the rolling die within a plane containing the first and second axes, in an in-feed direction substantially perpendicular to the first and second axes until the outer peripheral surface of the rolling die engages the outer peripheral surface of the workpiece at a near net shaped center distance establishing an initial center distance between the first and second axes when the workpiece and the rolling gear die are initially engaged; and

(j) continuing to advance the workpiece in the in-feed direction by an additional increment of center distance thereby deforming the profile surfaces of each gear tooth resulting in final net shape of the teeth.

40. A method of producing a rolling die for, in turn, producing a full form net shape roll finished contacting machine element from a near net shape workpiece of powder metal having an initial peripheral contoured surface comprising the steps of:

(a) providing a cylindrical grinding wheel having an initial outer peripheral surface generally shaped to correspond to the space between two adjacent teeth of a rolling die and rotatable about an axis;

(b) dressing the grinding wheel by advancing a peripheral edge of a disk-shaped dressing tool into engagement with the initial outer peripheral surface of the grinding wheel to remove material therefrom to thereby produce a grinding wheel final profile with a desired contoured outer surface;

(c) supporting on an axis which lies in a plane parallel to the plane of the grinding wheel axis but perpendicular to the grinding wheel axis a cylindrical rolling die blank having a plurality of circumferentially spaced near net shaped teeth, each pair of adjacent teeth having opposed gear tooth surfaces and a common root/fillet region therebetween;

(d) advancing the grinding wheel radially toward and into engagement with the rolling die blank such that the contoured outer surface thereof engages the opposed gear tooth flanks and the common root/fillet region between two adjacent teeth of the rolling die blank;

(e) simultaneously with step (d), rotating the grinding wheel about its axis to produce a final gear tooth profile for the opposed gear tooth surfaces and the common root/fillet region;

(f) withdrawing the grinding wheel from engagement with the rolling die blank;

(g) rotating the rolling die blank on its axis by an increment equal in arc length to the pitch between adjacent teeth thereof so that the grinding wheel is aligned with the opposed gear tooth surfaces and common root/fillet region of the next successive pair of adjacent teeth of the rolling die blank; and

(h) repeating steps (d), (e), (f), and (g) until all of the teeth of the rolling die blank have been ground to the desired shape of the rolling die.

41. A method of producing a full form net shaped gear from a near net shape workpiece having an initial outer peripheral contoured surface and including a plurality of gear teeth, each gear tooth having a gear tooth flank with a nominally involute surface and a root/fillet region with a trochoidal surface, the method comprising the steps of:

(a) providing a cylindrical grinding wheel having an outer peripheral surface and rotatable about an axis;

(b) dressing the grinding wheel by advancing a dressing tool into engagement with the outer peripheral surface to remove material therefrom to thereby produce a grinding wheel profile having a desired contoured outer surface;

(c) supporting on an axis which lies in a plane parallel to the plane of the grinding wheel axis but perpendicular to the grinding wheel axis a cylindrical rolling die blank having a plurality of circumferentially spaced near net shaped teeth defining an arcuate pitch length between adjacent teeth, each pair of adjacent teeth having opposed gear tooth surfaces and a common root/fillet region therebetween;

(d) advancing the grinding wheel radially toward and into engagement with the rolling die blank such that the contoured outer surface thereof engages the opposed gear tooth surfaces and the common root/fillet region between two adjacent teeth of the rolling die blank;

(e) simultaneously with step (d), rotating the grinding wheel about its axis to produce a final gear tooth profile for the opposed gear tooth surfaces and its common root/fillet region;

(f) withdrawing the grinding wheel from engagement with the rolling die blank;

(g) rotating the rolling die blank on its axis by an increment equal in arc length to the pitch between adjacent teeth thereof so that the grinding wheel is aligned with the opposed gear tooth surfaces and common root/fillet region of the next successive pair of adjacent teeth of the rolling die blank;

(h) repeating steps (d), (e), (f), and (g) until all of the teeth of the rolling die blank have been ground to the desired shape and resulting in a finished rolling die;

(i) rotatably supporting the finished rolling die on a first axis a rolling die having an outer peripheral contoured surface extending between generally parallel spaced lateral surfaces transverse to the first axis, the

rolling die including a plurality of teeth, each including a gear tooth flank with opposed involute surfaces and a gear tooth tip surface;

(j) rotatably supporting the workpiece on a second axis distant from and parallel to the first axis;

(k) advancing the rolling die in an in-feed direction generally perpendicular to the first and second axes such that the rolling die meshingly engages with the workpiece,

(l) rotating the rolling die while engaged with the workpiece;

(m) rolling the gear teeth surfaces of the workpiece to a desired outer peripheral profiled shape while engaged with the rolling die having an outer peripheral profiled surface while holding the workpiece at the uniform metastable austenitic temperature, the gear teeth surfaces undergoing densification, plastic deformation, and strengthening as a result of the rolling and sliding operation;

(n) while performing step (l), maintaining continuous conjugacy between the rolling die and the workpiece with the involute surface of each tooth of the rolling die engaging the involute surface of a mating tooth of the workpiece and the tooth tip of the rolling die engaging the trochoidal root/fillet surface of a mating tooth of the workpiece; and

(o) continuing to advance the rolling die in the in-feed direction thereby deforming the surface of each gear tooth flank and of a corresponding root/fillet region until a final net shape of each gear tooth and of each root/fillet region is achieved, and

(p) continuing to perform steps (i), (j), (k), (l), (m), and (n) with the rolling die and workpiece meshingly engaged, thereby deforming the

involute and trochoidal root/fillet surfaces of each tooth of the workpiece resulting in a final net shape of all of the teeth thereof.

42. The process set forth in claim 41

wherein step (e) includes the steps of:

(q) radially compacting the material in the gear teeth surface layers resulting in a collapse of the pores initially existing in the gear teeth surface regions with resulting densification of the gear teeth surface regions; and

(r) plastically deforming the gear teeth surface layers by causing lateral material flow of the gear teeth surface layers as a result of the operation of rolling in the metastable austenitic temperature range.

43. A method of producing a full form net shaped gear from a near net shape workpiece having an initial outer peripheral contoured surface and including a plurality of teeth, each having a tooth flank with a nominally involute surface and a root/fillet region with a trochoidal surface, the method comprising the steps of:

(a) rotatably supporting on first and second generally parallel spaced axes, first and second rolling dies, each having an outer peripheral contoured surface extending between generally parallel spaced lateral surfaces transverse to the first axis, each rolling die including a plurality of teeth, each tooth including a tooth flank with opposed involute surfaces and a tooth tip surface;

(b) rotatably supporting the workpiece on a third axis distant from and parallel to the first and second axes;

(c) advancing the first and second rolling dies, within a common plane generally containing the first, second, and third axes in respectively

opposite in-feed directions generally perpendicular to the third axis until the rolling die meshingly engages with the workpiece,

(d) rotating the rolling dies about their associated first and second axes while engaged with the workpiece;

(e) rolling the gear teeth surfaces of the workpiece to a desired outer peripheral profiled shape while engaged with the rolling die having an outer peripheral profiled surface while holding the workpiece at the uniform metastable austenitic temperature, the gear teeth surfaces undergoing densification, plastic deformation, and strengthening as a result of the rolling and sliding operation;

(f) while performing step (d), maintaining continuous conjugacy between each of the rolling dies and the workpiece with the involute surface of each tooth of each of the rolling dies engaging the involute surface of a mating tooth of the workpiece and the tooth tip of each of the rolling dies engaging the trochoidal root/fillet surface between adjacent mating teeth of the workpiece;

(g) continuing to advance each of the rolling dies in the in-feed direction thereby deforming the surface of each tooth flank and of a corresponding root/fillet region until a final net shape of each tooth and of each root/fillet region is achieved, and

(h) continuing to perform all of the preceding steps with the rolling dies and workpiece meshingly engaged, thereby deforming the involute and trochoidal root/fillet surfaces of all of the teeth of the workpiece resulting in a final net shaped machine element.

44. The process set forth in claim 43

wherein step (e) includes the steps of:

- (i) radially compacting the material in the gear teeth surface layers resulting in a collapse of the pores initially existing in the gear teeth surface regions with resulting densification of the gear teeth surface regions; and
- (j) plastically deforming the gear teeth surface layers by causing lateral material flow of the gear teeth surface layers as a result of the operation of rolling and sliding in the metastable austenitic temperature range.

45. A method as set forth in claim 43 including the step, before

step (c) of:

- (i) advancing the workpiece in a through-feed direction parallel to the first, second, and third axes such that the outer peripheral profiled surface of the workpiece engages the outer peripheral profiled surface of each of the rolling dies and continues to advance until the workpiece is positioned substantially coextensive with the rolling dies in the through-feed direction.

46. A method as set forth in claim 44

wherein step (c) includes the steps of:

- (i) simultaneously with step (h) after the workpiece and rolling die are substantially enmeshed, advancing the rolling die within a plane containing the first and second axes, in an in-feed direction substantially perpendicular to the first and second axes until the outer peripheral surface of the rolling die engages the outer peripheral surface of the workpiece at a near net shaped center distance establishing an initial center distance between the first and second axes when the workpiece and the rolling gear die are initially engaged; and

(j) continuing to advance the workpiece in the in-feed direction by an additional increment of center distance thereby deforming the profile surfaces of each gear tooth resulting in final net shape of the teeth.